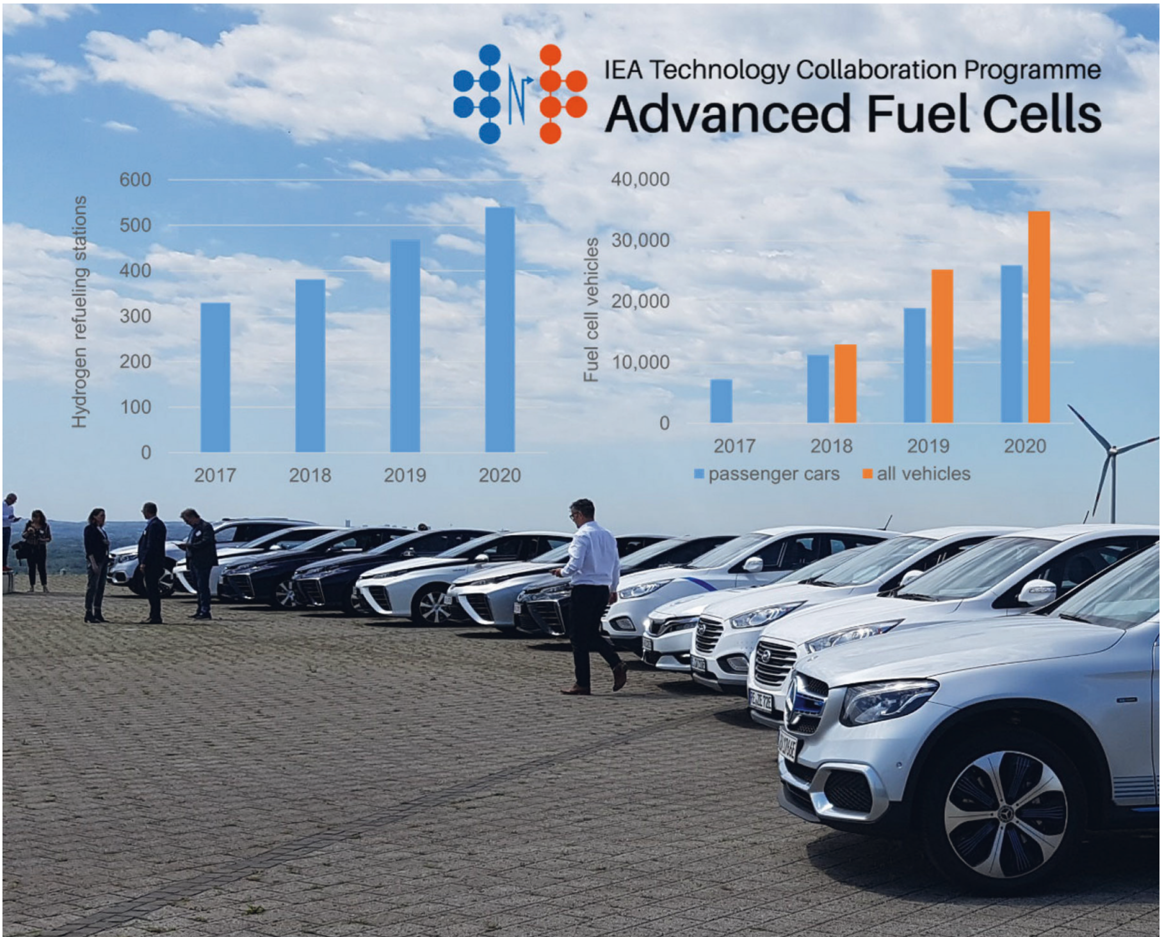

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Remzi Can Samsun, Laurent Antoni, Michael Rex, Detlef Stolten

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Abstract

The number of fuel cell-powered vehicles being used for road transport is rapidly increasing around the world. In order to determine their present deployment status, the International Energy Agency (IEA) Advanced Fuel Cells Technology Collaboration Programme (AFC TCP) performs an annual data collection across its member countries and beyond. This report captures the current state of the country-base deployment of fuel cell vehicles globally as of the end of 2020. Furthermore, an overview of the worldwide hydrogen refueling station infrastructure is presented. Based on the most recent numbers and those from more recent years, the development trends are analyzed. Furthermore, information on selected passenger vehicles operating with fuel cell technology is updated and accompanied by an analysis of different incentives and vehicle prices in various countries. Apart from the number of hydrogen refueling stations, available information on the stations, such as pressure levels and links to their locations, are presented. Finally, the report reviews the defined targets, projections and visions regarding the future development perspectives of fuel cell vehicles and hydrogen refueling stations.

Based on the results of the data collection, the AFC TCP estimates a total of 34,804 fuel cell vehicles and 540 hydrogen refueling stations to be in operation as of the end of 2020. The total number of fuel cell vehicles is made up of 25,932 passenger cars, which saw a 37% increase in 2020. Having undergone a strong increase in a single year, South Korea now has the majority of passenger cars equipped with fuel cell technology on its roads. China still leads global markets for buses and medium-duty trucks. Moreover, the public refueling stations in Japan, Germany, China, and the U.S. represent a significant share of 63% of the total number of stations worldwide.

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1. INTRODUCTION

Hydrogen produced using renewable sources has the potential to play a major role in achieving international greenhouse gas neutrality targets. Hydrogen enables the long-term storage of volatile renewable energy and can serve as a vector for the synergistic coupling of various sectors, such as power, transportation, heat, manufacturing, and chemicals. Thanks to the recently announced roadmaps and strategies on the regional, national and international levels, hydrogen technologies are currently enjoying a central position in energy- and climate-related discourse.

Fuel cell technologies enable the highly efficient conversion of hydrogen into heat and power. Amongst other applications, fuel cells in the transportation sector can extend the portfolio of electric vehicles. Here, fuel cell vehicles present a decisive advantage in terms of refueling times over battery-electric options, as hydrogen can be refueled in comparable time periods to conventional liquid fuels. Although several fuel cell vehicle models are already available for purchase, their high prices, due to low production volumes, have kept their overall numbers limited.

The goal of this report is to present the present status of fuel cell vehicle (FCV) deployment and the worldwide hydrogen refueling station infrastructure as of early 2021. Based on data collected from a detailed survey, the main status and development trends are analyzed. Furthermore, future development perspectives are presented based on publicly-released roadmaps, strategies and visions.

The structure of this document is as follows:

- The second chapter focuses on fuel cell vehicles. In the first section, the results of the AFC TCP survey on the number of fuel cell vehicles are presented and discussed, including development trends over the last four years. This is followed by an overview of selected fuel cell vehicles for passenger car applications, which represents the highest market share. Finally, subsidy schemes and purchasing prices of fuel cell vehicles in selected countries are discussed.
- The third chapter addresses hydrogen refueling stations. After presenting the status of the infrastructure, the development trend of the refueling infrastructure between 2017 and 2020 is analyzed. Furthermore, the results of the chapters on the vehicles and refueling stations are analyzed together. This chapter also includes further data on refueling stations, such as pressure levels, the number of public stations, information on location maps, and additional information on hydrogen refueling stations.
- The fourth chapter compiles selected announcements from different sources to present a complete picture of the defined targets of fuel cell vehicle deployment and hydrogen refueling station infrastructure development. This chapter also outlines the visions of leading sectoral institutions, such as the Hydrogen Council, Hydrogen Europe

and the California Fuel Cell Partnership. At the end, all numbers are placed in a timeline to give the reader a complete overview of possible future developments.

- The final chapter concludes the report with a brief summary of the main findings.

2. FUEL CELL VEHICLES

This chapter presents the data collected in the latest AFC TCP survey regarding the registered number of fuel cell vehicles in road transport. After discussing the continent-, country- and vehicle type-based figures, the development trends are discussed. This is followed by an overview of vehicle specifications and subsidy schemes.

2.1. AFC TCP SURVEY RESULTS ON THE NUMBER OF FUEL CELL VEHICLES

The latest AFC TCP survey was begun in early 2021 to capture the status of registered fuel cell vehicles as of the reporting date of 31/12/2020. This survey represents the fourth in the series, following those performed in 2018 [1], 2019 [2] and 2020 [3], which also captured the status as of December 31 of those years.

The survey primarily consists of input from the AFC TCP member countries, supported by the FCH 2 JU Programme Office for European data. At the same time, information published in open sources or reports, such as the IPHE Country Updates, complemented the database. Citations [4]–[28] list the sources of the data collection. In a few cases, the cited data refers to other dates than the reporting date of 31/12/2020, which is mentioned in the corresponding footnote.

An analysis of the collected data indicates that 34,804 fuel cell vehicles (FCVs) of all types were in operation worldwide as of the end of 2020. This total includes passenger cars,[1] buses,[2] light commercial vehicles,[3] and medium-[4] and heavy-duty trucks.[5] Figure 1 presents the number of vehicles in different countries. It can be seen that most of the vehicles can be found in South Korea, followed by the U.S., China and Japan. This year, South Korea took the lead for the first time, replacing the U.S. In order to demonstrate the continental distribution, Figure 2 shows that 65% of the vehicles are in Asia, followed by 27% in North America, and 8% in Europe. The vehicle mix is dominated by passenger cars (74.5%), followed by buses (16.2%), and medium-duty trucks (9.1%), as is shown in Figure 3.

[1] Fuel cell-electric vehicles (FCEVs) in the category light-duty vehicles (passenger cars and vans) such as the Toyota Mirai, Hyundai Nexo, Honda Clarity fuel cell, Mercedes-Benz GLC F-CELL, etc., with the maximum mass not exceeding 3.5 tonnes and there being no more than eight seats in addition to the driver's seat.

[2] Carriage of passengers with more than eight seats in addition to the driver's seat.

[3] Vehicles for the transport of goods and with a maximum mass not exceeding 3.5 tonnes, e.g., the Renault Kangoo, Master, Mercedes-Benz Sprinter, Volkswagen Crafter, Caddy, Ford Transit, etc.

[4] Trucks with a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes; trailers and semitrailers with a maximum mass exceeding 3.5 tonnes, but not exceeding 10 tonnes.

[5] Trucks with a maximum mass exceeding 12 tonnes; trailers and semitrailers with a maximum mass exceeding 10 tonnes.

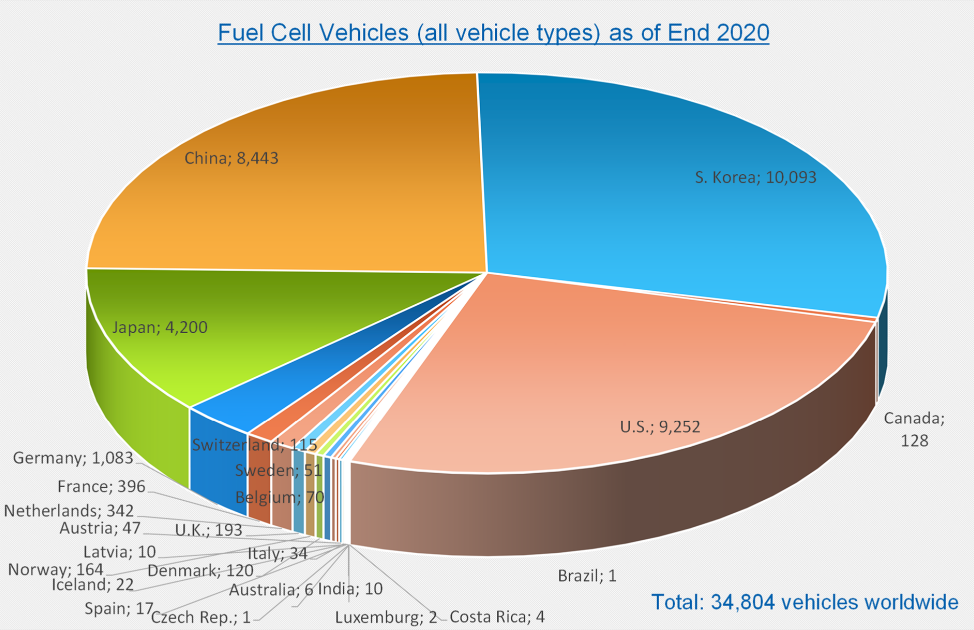

FIGURE 1. DISTRIBUTION OF FUEL CELL VEHICLES ON THE ROAD BY COUNTRY AS OF THE END OF 2020.

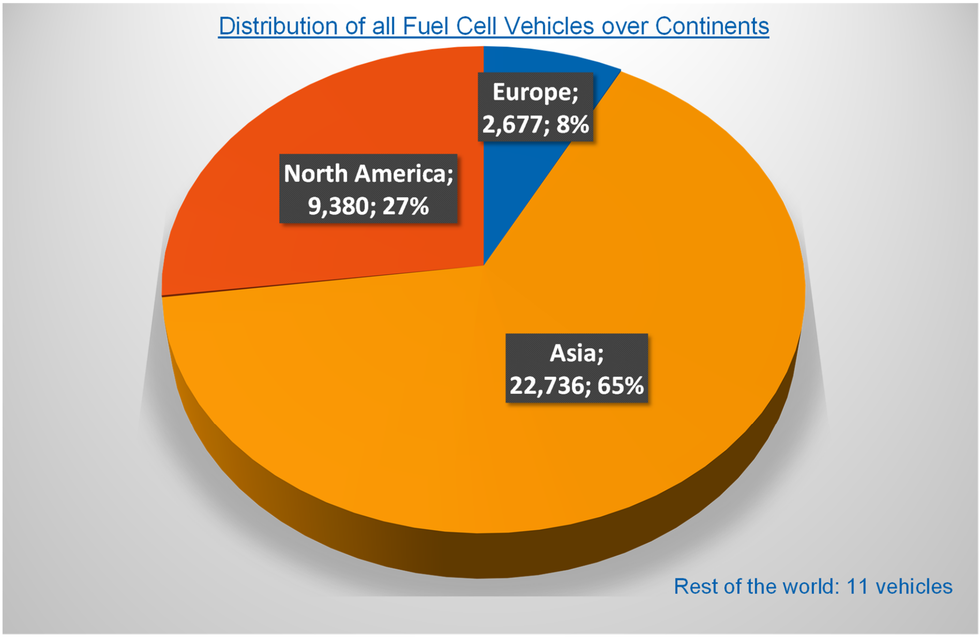

FIGURE 2. DISTRIBUTION OF ALL FUEL CELL VEHICLES BY CONTINENT AS OF THE END OF 2020.

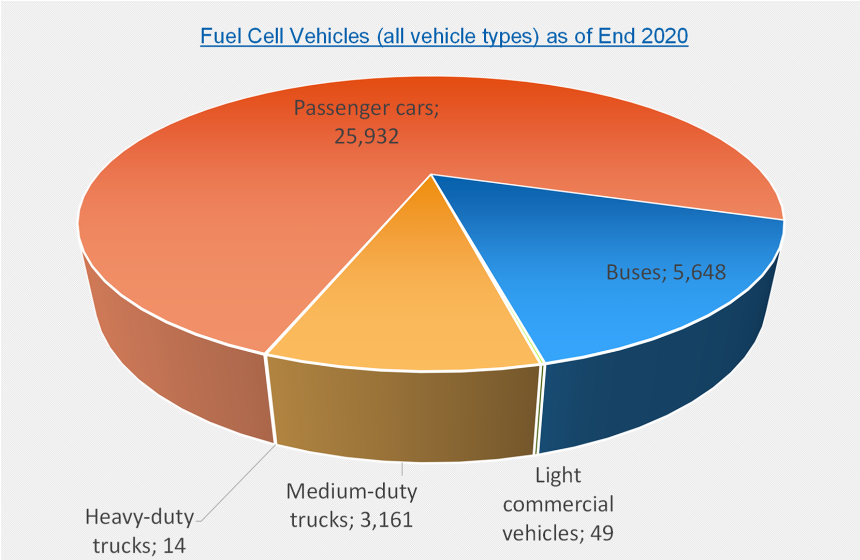

FIGURE 3. SHARE OF DIFFERENT VEHICLE TYPES ACROSS THE TOTAL NUMBER OF FUEL CELL VEHICLES (FCVS) WORLDWIDE.

The continental distribution exhibits a similar trend for passenger cars (FCEVs: Fuel cell electric vehicles) as well (see Figure 4). Again, most passenger cars are in Asia (55%), followed by North America (36%) and Europe (9%). In comparison to the previous year [3], the Asian share increased by nine percentage points, whereas the shares of North America and Europe both dropped by seven and two percentage points, respectively.

As is depicted in Figure 5, the North American market is primarily composed of fuel cell vehicles in the U.S., with a share of 98.7% comprising 9,188 cars. Meanwhile, 128 vehicles were in operation in Canada. The increase in the U.S. total was limited by 15% this year, in comparison to 37% in the previous one. More than 99% of the fuel cell vehicle fleet in the U.S. is composed of passenger cars.

Similarly, Figure 6 provides insight into the distribution of passenger cars in Asia. The main players in this category are South Korea and Japan, with no contribution from China, despite being the third highest FCV penetration country, accounting for 24% of the total number worldwide. Comparing the results with the previous year's survey [3], it can be seen that the number of passenger cars in South Korea almost doubled in a single year, with a very strong increase of 98%. With its 10,041 passenger cars, South Korea also leads this category with a share of 38.7% of the worldwide fleet, followed by the U.S. (35.4%) and Japan (15.8%). Together, these three countries contribute almost 90% of the global FCEV passenger car fleet.

In Europe, the fleet is dominated by passenger cars in Germany and France, as is shown in Figure 7, with 56.4% of European FCEVs spanning these two countries. The Netherlands, U.K., Norway, and Denmark follow these.

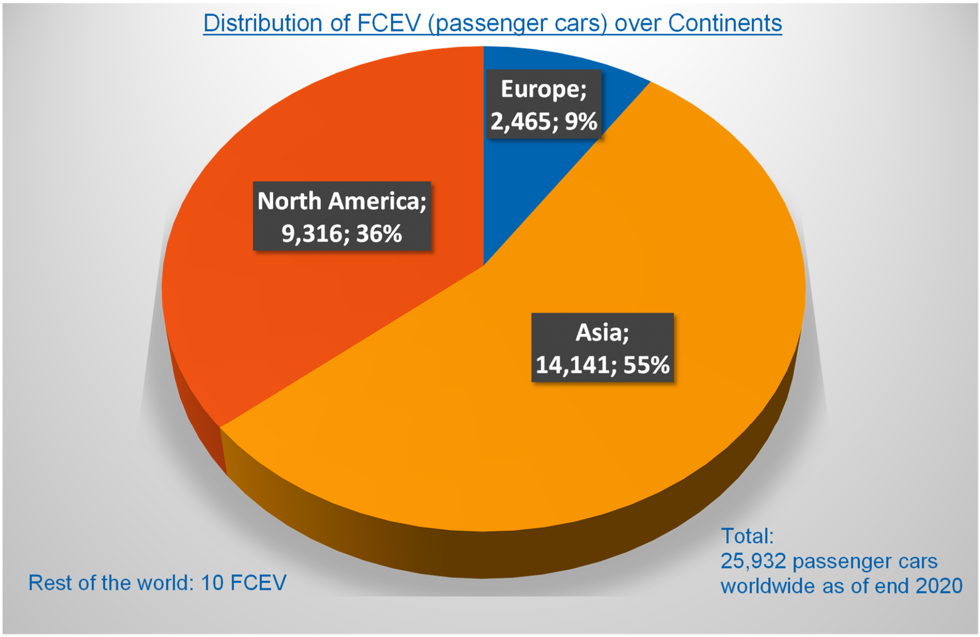

FIGURE 4. DISTRIBUTION OF FCEV PASSENGER CARS ACROSS DIFFERENT CONTINENTS.

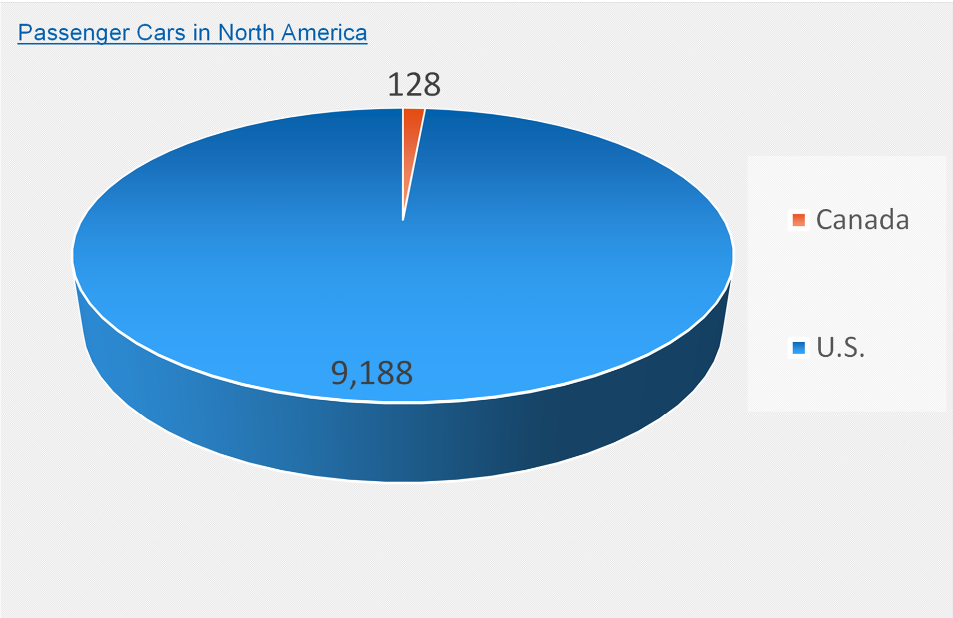

FIGURE 5. DISTRIBUTION OF PASSENGER CARS ACROSS COUNTRIES IN NORTH AMERICA.

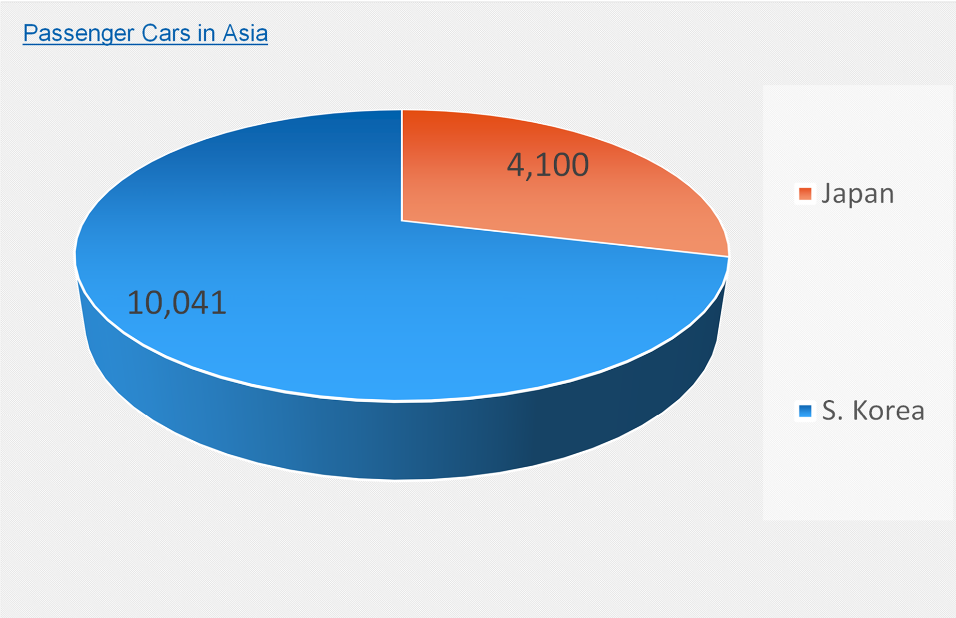

FIGURE 6. DISTRIBUTION OF PASSENGER CARS ACROSS COUNTRIES IN ASIA.

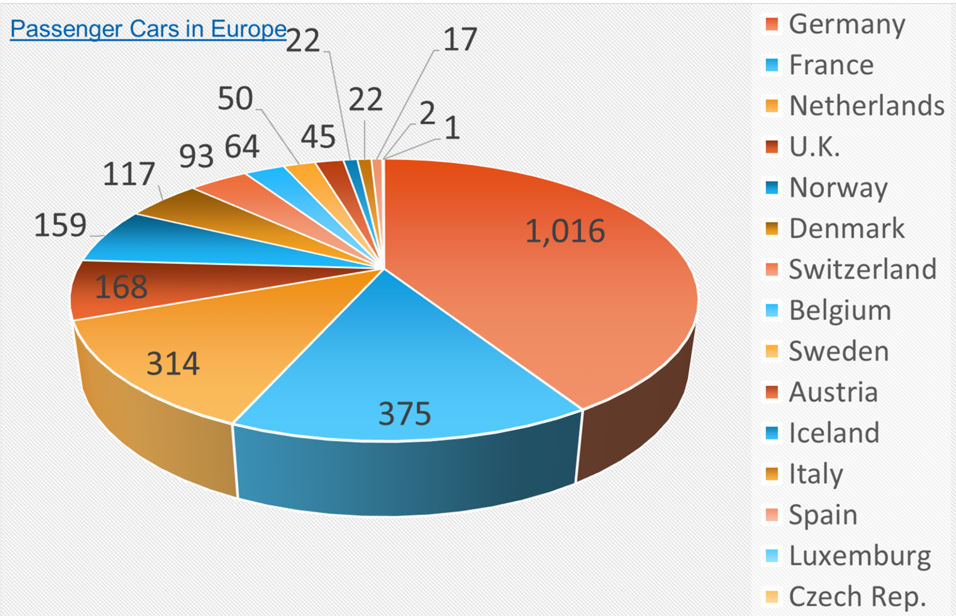

FIGURE 7. DISTRIBUTION OF PASSENGER CARS ACROSS COUNTRIES IN EUROPE.

The next analysis will focus on the 5,648 fuel cell buses with the help of Figure 8 and present the distribution of fuel cell buses across the continents. At present, 97% of the buses are operated in Asia, leaving little space for Europe and North America. Within Asia, 5,290 of the 5,452 total buses are operated in China. A similar analysis can also be made for medium-duty trucks, with 3,153 of the 3,161 medium-duty trucks in Asia being in China. Together, these two categories make up the Chinese FCV market. As is clearly presented in Figure 9, 93.7% of the fuel cell buses and 99.7% of the medium-duty fuel cell trucks worldwide are in China. With these two segments, China contributes to the global FCV fleet by accounting for every fourth vehicle with a completely different vehicle type profile than the rest of the world. It has also been reported that 50 heavy-duty trucks were produced in China, but had not been registered by the end of 2020 [29].

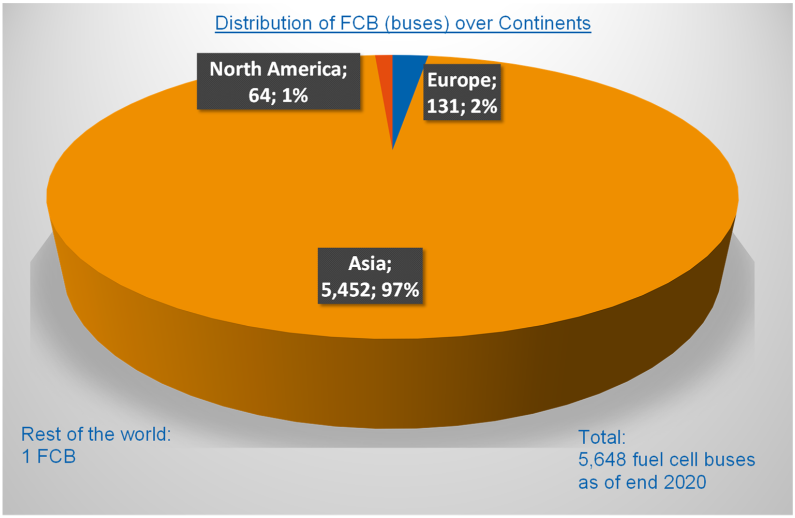

FIGURE 8. DISTRIBUTION OF FUEL CELL BUSES (FCB) ACROSS CONTINENTS.

The data collection includes two further vehicle categories, namely light commercial and heavy-duty vehicles, which have not been analyzed up until this point. The light commercial vehicle category was introduced in the survey for the first time. In previous years, this category was included in passenger cars. The survey results indicate only 49 vehicles in this category around the world. It must be noted that in the case of some of the countries, e.g., France, light-duty vehicles are already included among the total passenger cars. Another challenge was to monitor the number of heavy-duty trucks, as many vehicles are prototypes that are being operated for demonstration projects, such as in the U.S. Therefore, the 14 vehicles reported in this category, specifically the 12 in Switzerland and two in the Netherlands, will be interpreted with uncertainty as to the possibility of there being a higher number than that reported here.

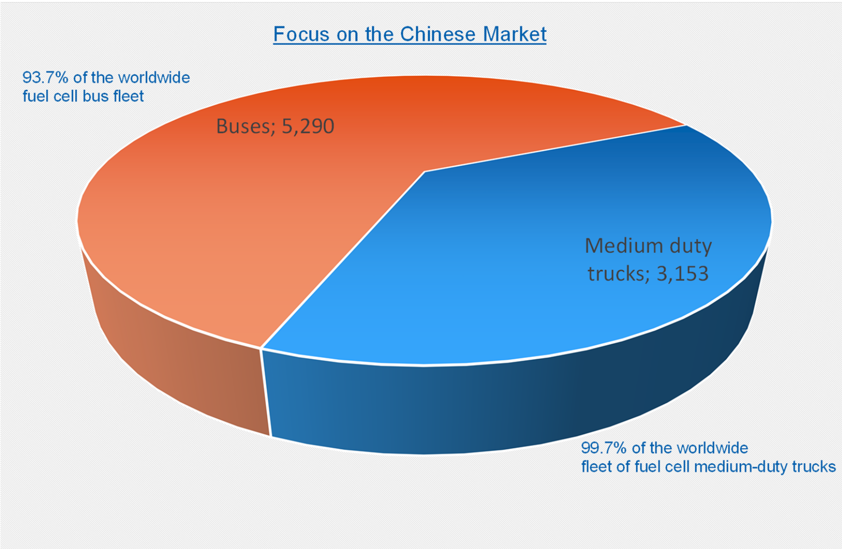

FIGURE 9: FOCUS ON THE CHINESE MARKET

Fundamentally, Figure 10 displays the development trend for the number of FCEVs worldwide from 2017–2020. In 2017, only passenger cars were considered, as the total numbers of other vehicle types were very low [1]. The 2018 survey introduced a further category, estimating the total number of all fuel cell vehicles (FCV), taking the market development in China concerning commercial vehicles into account [2]. The number of registered passenger cars already showed an increase of 56% at the end of 2018. By late 2019, this trend had continued with a stronger increase of 69% for passenger cars in one year [3]. The newest survey results indicate a weaker increase of 37% for the year 2020. In 2019, the number of newly-registered passenger cars was 7,700; in 2020, it totaled 7,000. Thus, the absolute increase in the number of passenger cars was comparable.

The number of all FCVs showed a similar increasing trend of 38% in 2020, which is much slower than the increase in 2019 of 95%. In 2019, the strong increase was driven by China. The Hydrogen and Fuel Cell Industry Monthly Report from January 2021 [29] points out that sales in China slowed down considerably due to changes in the national subsidy policy and the overall market trend starting to improve again in September after five Departments announced the new policy.

The most important growth factor for 2020 was the increase in the number of passenger cars in South Korea. More than half of the overall increase in the number of fuel cell vehicles around the world was accounted for by the increase in this figure.

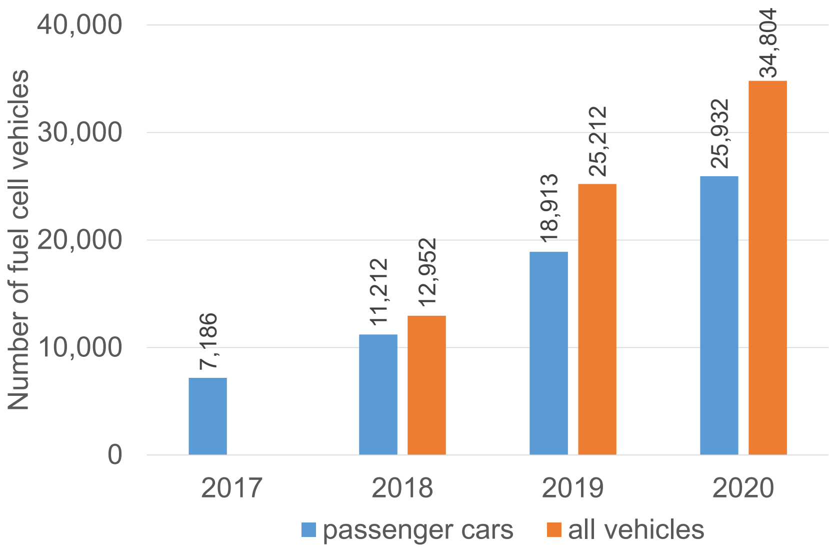

FIGURE 10. DEVELOPMENT OF THE NUMBERS OF FUEL CELL VEHICLES DEPLOYED WORLDWIDE.

2.2. INFORMATION ON SELECTED VEHICLES

Technical data on selected (FCEV) passenger car models that are currently available for purchase or lease in different countries is listed in Table 1, based on the information provided by the car manufacturers. In comparison to last year's report, the table includes the specifications of the Toyota Mirai in its second generation, the first of which went on sale in late 2020. The specifications of the Hyundai Nexo, Honda Clarity Fuel Cell and Mercedes-Benz GLC F-Cell are the same as those in last year's report [3].

TABLE 1. TECHNICAL SPECIFICATIONS OF THE TOYOTA MIRAI [30], [31], HYUNDAI NEXO [32], [33], HONDA CLARITY FUEL CELL [34], [35], AND MERCEDES-BENZ GLC F-CELL [36], [37].

FCEV	Toyota Mirai	Hyundai Nexo	Honda Clarity Fuel Cell	Mercedes-Benz GLC F-Cell
Fuel cell stack	330 cells 102 g cell weight 128 kW max. output 5.4 kW/l volume power density 5.4 kW/kg mass power density 29 l volume / 32 kg weight	95 kW 440 cells 3.1 kW/l power density @ 0.6 V 60% system efficiency	103 kW 358 cells 33 l volume 52 kg weight	
Battery	Lithium-ion 310.8 V power output 4 Ah / 1.24 kWh capacity 44.6 kg battery pack weight	Lithium-ion polymer 240 V voltage 40 kW power output 1.56 kWh output 95.3% charge / discharge efficiency	Lithium-ion 346 V voltage	Lithium-ion 13.5 kWh capacity
Electric motor / generator	Permanent magnet, synchronous 134 kW max. power 300 Nm max. torque	Permanent magnet motor 120 kW power output 395 Nm. max. torque	AC permanent magnet synchronous motor 130 kW power output 300 Nm max. torque	Asynchronous machine 155 kW power output 365 Nm max. torque
Performance	175 km/h max. speed 9.2 s 0–100km/h acceleration	179 km/h max. speed 9.2 s 0–100 km/h acceleration 7.4 s 80–120 km/h acceleration -30 °C cold start temperature	165 km/h maximum speed 9.0 s 0-100 km/h acceleration	160 km/h maximum speed
Fuel consumption / Driving range	0.89 kg/100 km combined (WLTP) 650 km	666 km WLTP 756 km NEDC	650 km NEDC	1 kg / 100 km hydrogen 478 km NEDC hybrid mode (50 km battery only)
Tank system	700 bar nominal working pressure 875 bar max. filling pressure 5.6 kg fuel tank capacity 24 kg tank weight Three tanks	6.33 kg hydrogen 156.6 l overall capacity, 3 tanks, each 52.2 l	700 bar 5.46 kg hydrogen 141 l overall capacity, 2 tanks, 24 l and 117 l	700 bar 4.4 kg hydrogen
Weight	1,920–1,950 kg curb weight 2,415 kg gross vehicle weight	2,340 kg gross vehicle weight 1,814–1,873 kg curb weight	1,875 kg curb weight	
Exterior	4,975 mm overall length 1,885 mm overall width 1,480 mm overall height 2,920 mm wheelbase 0.29 drag coefficient	4,670 mm overall length 1,860 mm overall width 1,630 mm overall height 2,790 mm wheelbase 0.329 drag coefficient	4,915 mm overall length 1,875 mm overall width 1,480 mm overall height 2,750 mm wheelbase	4,671 mm overall length 2,096 mm overall width 1,653 mm overall height 2,873 mm wheelbase

2.3. SUBSIDY SCHEMES AND PURCHASE PRICES IN SELECTED COUNTRIES

This section highlights different incentives for purchasing or leasing fuel cell vehicles in selected countries and lists the vehicle prices.

There are different subsidy schemes for fuel cell vehicles in the U.S. The Internal Revenue Service (IRS) provides a tax credit of up to USD 8,000 at the federal level for the purchase of qualified light-duty fuel cell vehicles, the subsidy amount being based on the vehicle's fuel economy. Based on vehicle weight, tax credits are also available for medium- and heavy-duty fuel cell vehicles [38]. In addition, different states offer subsidies. The Clean Vehicle Rebate Project, administered by the CSE for the California Air Resources Board, offers electric vehicle rebates for the purchase or lease of new, eligible zero-emissions and plug-in hybrid light-duty vehicles in California. The Honda Clarity Fuel Cell, Hyundai Nexo, and Toyota Mirai FCEVs are eligible for USD 4,500 rebates [39]. Similarly, the Connecticut Hydrogen and Electric Automobile Purchase Rebate Program (CHEAPR) offers rebates against the incremental costs of the purchase or lease of FCEVs, among others. For fuel cell vehicles, the manufacturer suggested retail price may not exceed USD 60,000; the rebate amount totals USD 5,000 for fuel cell vehicles [40].

The subsidies for purchasing fuel cell vehicles in Japan vary from JPY 1,173,000 (Toyota Mirai "new version") to JPY 2,100,000 (Honda Clarity Fuel Cell); in addition, some local governments offer subsidies [41]. The purchasing price of a Mirai (new version) from Toyota varies between JPY 7,100,000 and JPY 8,100,000 [42], whereas the Clarity Fuel Cell from Honda has a purchasing price of JPY 7,800,000 [43].

FCEVs receive a subsidy of up to EUR 6,000 in Spain [44], with the total price of one there being around EUR 72,000 [21].

The Eco bonus in Italy applies from zero to 20 g/km of CO_2 and ranges between EUR 10,000 and EUR 6,000, depending on whether the purchase is made with or without scrapping. Under this scheme, the maximum price of new cars purchased must not exceed EUR 61,000 [45].

In France, the financial incentive for purchasing FCEVs was increased from EUR 6,000 to EUR 7,000 from 01/06/2020 [46].

In Austria, the Hyundai NEXO is only available for customers with a professional connection to the hydrogen industry [47], whereas the Toyota Mirai is publicly available for EUR 59,900 [48]. The same subsidies apply for FCEVs as for BEVs: new Passenger cars for private individuals receive a subsidy of EUR 3,000 from federal funding and EUR 2,000 EUR from the car importer. For companies and organizations, the subsidy is EUR 2,000, with transporters of up to 2 tonnes also receiving this support. The subsidy can be a maximum of 30% of the purchase price. The maximum allowed purchase price corresponds to EUR 60,000 for private individuals and companies based on the gross list price. The requirement is the proof that the hydrogen used originates from renewable sources only. In addition, tax benefits apply to FCEVs. There is an exemption from the standardized consumption tax (NoVa), the engine-related insurance tax, as well as the vehicle tax. Moreover, an input tax deduction is applied if the purchase price is lower than EUR 40,000. In addition, regional subsidies have been published for Austria [49]–[53].

In Denmark, hydrogen cars are exempt from initial registration taxes [54]. The Toyota Mirai is available for prices between DKK 499,990–589,990 in this country [55].

In Sweden, the bonus malus system for vehicles that emit zero CO_2 has been in place since 01/07/2018 and only applies to new vehicles that are taxed and insured, and has consequently been put into effect on or after that date according to the Swedish vehicle register. FCEVs are subject to SEK 60,000 when sold new [56]. The purchasing price of Hyundai Nexo is SEK 860,000–880,000, whereas the price of Toyota Mirai is around SEK 700,000 [57].

The drivers of FCVs in Switzerland are exempt from performance-related heavy vehicle charges and petroleum taxes. The performance-related heavy vehicle charge totals CHF 0.0228 tkm for Euro 6 vehicles. In the case of heavy-duty trucks in the 40 t weight class driving 100,000 km per year, the saving corresponds to CHF 91,200, with the petroleum tax being CHF 0.759 per liter of fuel. Assuming the same mileage as above and a fuel consumption of 32 l/km, an additional annual saving of CHF 24,300 can be realized under this exemption [58].

The prices of available fuel cell vehicles in Canada are CAD 73,000 for the Hyundai Nexo and CAD 73,800 for the Toyota Mirai, with a federal incentive of CAD 5,000 applying to FCEVs. In addition, various incentives are available in different regions. In Quebec, the incentives vary between CAD 3,000 and CAD 8,000 depending on the vehicle manufacturer's suggested retail price (MSRP). In British Columbia, the incentives amount to CAD 3,000 to a maximum vehicle MSRP, whereas CAD 5,000 obtains in Yukon [59]–[62].

The basic version of the Toyota Mirai, currently in its second generation, has a starting price of EUR 63,900 in Germany [63]. The recommended retail price of the Hyundai Nexo is EUR 77,290 [64]. Another available FCEV model in Germany is the Mercedes GLC F-CELL, which is only leased based on a full-service model [65]. Currently, the Toyota Mirai is eligible for the environmental bonus by the BAFA (as of 19/04/2021) [66]. The interim report from 01/04/2021 shows that 189 applications for FCEVs were received up until that date [67], all of which were for the Hyundai models, with 170 for the current model NEXO and 19 for its predecessor ix35 Fuel Cell. By comparison, 313,879 applications were filed for pure electric vehicles and 234,208 for plug-in hybrids. Both Hyundai models were listed as eligible for the environmental bonus in the older versions of the BAFA, unlike the first-generation Mirai. Meanwhile, the second-generation Mirai is the only FCEV listed by the BAFA. In the present version, vehicles that are registered between 03/06/2020 and 31/12/2021 for the first time receive the innovation bonus (Innovationsprämie), in which the previous environmental bonus is doubled and the car manufacturer's part remains constant. Up to a BAFA list price of EUR 40,000, pure electric vehicles and FCEVs receive EUR 6,000 incentives from the federal government for purchasing, EUR 1,500 for leasing for 6–11 months, EUR 3,000 for leasing for 12–23 months, and EUR 6,000 for leasing for more than 23 months. On top of this, EUR 3,000 is provided by the car manufacturer, resulting in EUR 9,000 total incentive for purchasing a new vehicle. For a list price of between EUR 40,000 and EUR 65,000, which is relevant for the currently eligible FCEVs, the federal incentives drop to EUR 5,000 for purchasing and leasing for more than 23 months, EUR 1,250 for leasing for 6–11 months, and EUR 2,500 for leasing for 12–23 months. In this case, the car manufacturer's component corresponds to EUR 2,500. The latter window of incentive levels also applies to second-hand vehicles independent of the BAFA list price, which is the lowest net list price of the base model in Germany at market launch [68].

As noted in the previous section, incentives for purchasing FCEVs in China provided by the central government were terminated in April of 2020. The government intends to commence a new program in selected cities [69].

3. Hydrogen Refueling Stations

This chapter assesses the present worldwide hydrogen refueling station (HRS) infrastructure. At the end of 2020, 540 HRSs were in operation, including both public and private installations. A continent-based analysis reveals that most HRSs are concentrated to Asia, with a total of 278, followed by Europe, with 190, and 68 in North America. The country with the highest number of stations is Japan (137). Germany (90) and China (85) have the second and third place, respectively, in this ranking. The U.S. now occupies the fourth position instead of the third, having more or less undergone a stagnation, with 63 stations, ahead of South Korea (52) and France (38). The most remarkable changes were registered for China and Japan, each of which opened 24 new stations in 2020, followed by South Korea with 18, France with 13, and Germany with 9 new stations. The information sources are given in [70]–[85]. All data is current as of 31/12/2020 unless otherwise stated.

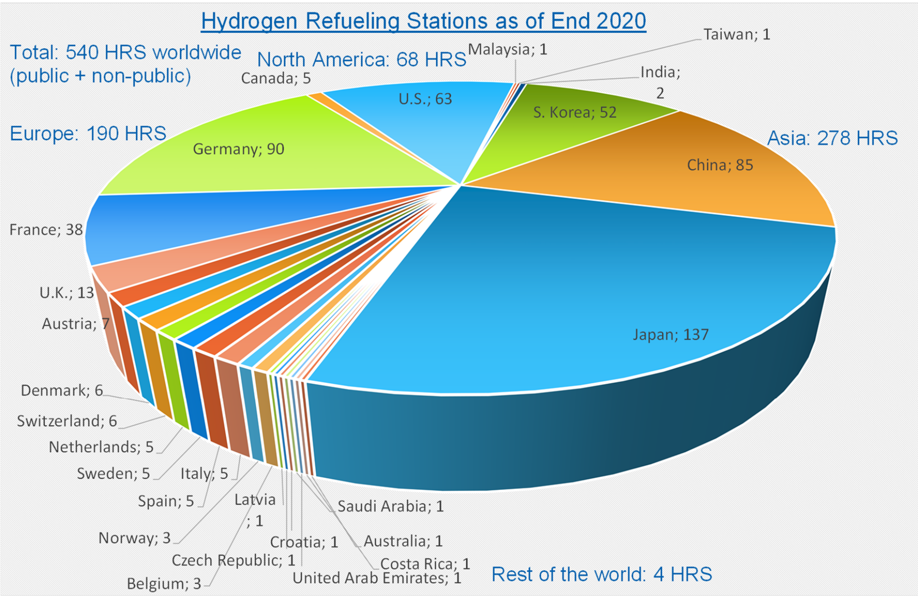

Figure 11. Country-based overview of hydrogen refueling stations (HRS) worldwide as of the end of 2020.

The available data does not enable an exact estimation of the share of public and private stations to be made. However, especially for countries with higher numbers of stations, the number of public stations is publicly available. The three countries with the highest numbers of publicly-available hydrogen refueling stations changed slightly in 2020. Japan (137) and Germany (90) are still in the first two places, whereas China is now in the third (66), followed by

the U.S. (46). This ranking is therefore the same as the total number of stations. In Germany and Japan, all stations are public. With these numbers, the publicly available HRSs in these four countries (242) represent 63% of the total stations (public and private) worldwide.
The total number of HRS around the world saw an increase of 15% in 2020. The increase was weaker than the 23% observed in 2019, but on the same level as that in 2018. The growth in the number of hydrogen refueling stations around the world over the 2017–2020 period is presented in Figure 12.

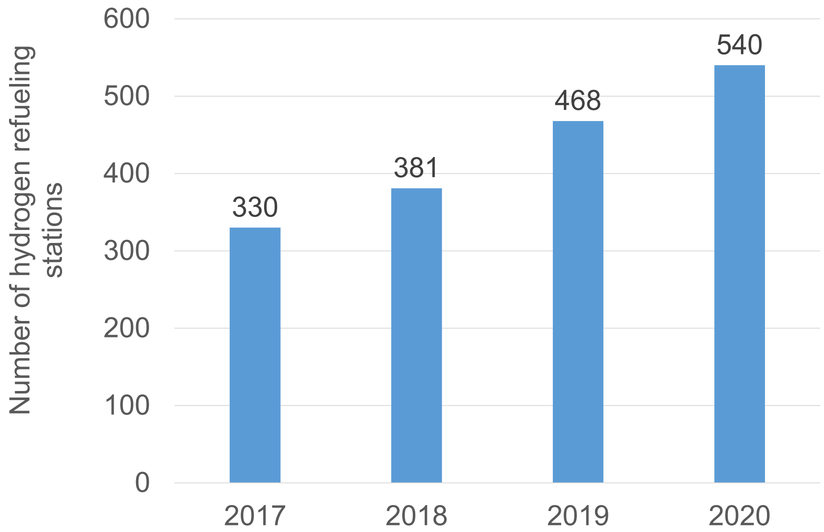

FIGURE 12. WORLDWIDE NUMERICAL DEVELOPMENT OF HRSS FOR 2017–2020.

As in the last year, based on the number of stations and vehicles, the total number of FCEVs per hydrogen refueling station could be calculated for the six countries with the highest numbers of HRSs. This theoretical analysis allocates the registered vehicles to a station in each country without considering the geographical location of the stations or the registry areas of the vehicles. As Figure 13 shows, the number of vehicles per station is currently nearing 200 in South Korea. The same ratio approaches 150 in the U.S. In the case of China, the number of vehicles per HRS is around 100. The Japanese ratio takes the fourth position, with about 30 vehicles per station. Germany and France can be put in a joint fifth place, with around 10 vehicles for each station. This diagram shows a strong discrepancy, with a factor of 20 between both extreme categories in South Korea on the one side and Germany and France on the other.

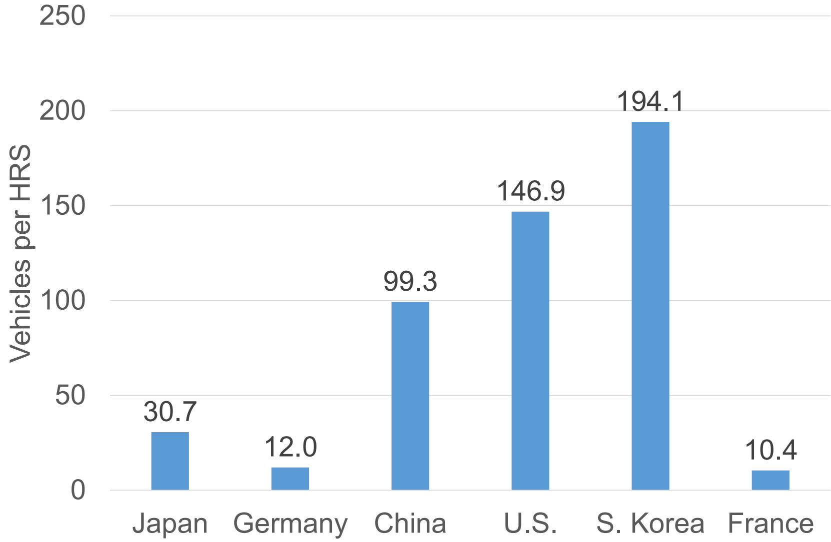

FIGURE 13. ANALYSIS OF THE NUMBER OF FCVS PER HRS IN THE SIX COUNTRIES WITH THE HIGHEST NUMBER OF HRSS AS OF THE END OF 2020. (JAPAN: HIGHEST NUMBER OF HRSS; FRANCE: LOWEST NUMBER AMONG THE TOP SIX COUNTRIES).

As noted above, it was not possible to distinguish between public and private (non-public) stations for each of the 540 in operation. For the sake of completeness, the partly available numbers are listed in Table 2, together with specifications on the pressure levels and links for station maps.

Most of the stations for passenger cars are operated at 700 bar. Stations for buses typically utilize 350 bar. The HRS Availability Map of the FCH JU / European Commission indicated 145 public HRS stations in Europe, from which 127 stations provide 700 bar for passenger cars, 46 provide 350, also for passenger cars, and 16 provide 350 bar for buses. It is clear that many stations offer more than one possibility [86].

Priem analyzed hydrogen delivery among 45 stations in Europe funded by the FCH 2 JU [87]. Nine of the 350-bar and three of the 700-bar stations operate with delivered hydrogen; six of the 350-bar and ten of 700-bar stations with on-site-produced hydrogen; six of the dual stations (350 and 700 bar) with delivered hydrogen, five with on-site-produced hydrogen; five stations at other pressure levels utilize trucked-in hydrogen and one further station at another pressure level produces hydrogen on-site.

Table 2. Number of HRSs, public stations, pressure levels and links for station locations [70]–[85].

Country	Number of HRSs	Public sta-tions	Notes	HRS locations
Japan	137	137	All: 700 bar	http://fccj.jp/hystation/in-dex.html#hystop
Germany	90	90	Mainly 700 bar, 7 dual (350/700)	https://h2.live/en
China	85	66	-	See attached map in the appendix
U.S.	63	46	350 bar and 700 bar	https://afdc.energy.gov/fuels/hydro-gen_locations.html
South Korea	52	NA	-	http://eng.h2korea.or.kr/
France	38	28	350 and 700 bar for vehicles, 200 bar for bikes	https://www.vighy-afhypac.org/
U.K.	13	10	2 x 350, 11 x dual	
Austria	7	5	Both 350/700 bar available in the country	https://h2.live/en
Switzerland	6	NA	-	
Denmark	6	6	-	https://brintbiler.dk/tankstationer/
Italy	5	1	Both 350/700 bar available in the country	
Spain	5	2	4 x 350, 1 x 700 bar	
Sweden	5	5	Mainly 700 bar, 2 dual (350/700); Green hydrogen supply in all stations	http://www.vatgas.se/tanka/sta-tioner/
Canada	5	3	700 bar for light-duty	
Netherlands	5	3	3x dual, 1x unknown, 1 x 350	
Belgium	3	2	1x dual, 1x 350, 1 x 700 bar	
Norway	3	NA	2 x 700, 1 x 350	
India	2	NA	350 bar	
Croatia	1	1	30 bar, for bicycles	
Australia	1	1	350 bar	
Costa Rica	1	NA	350 bar	
Czech Re-public	1	NA	350 bar, car and bus	
Malaysia	1	NA	dual	
Latvia	1	1	dual	
Saudi Arabia	1	NA	700 bar	
Taiwan	1	NA	-	
United Arab Emirates	1	NA	700 bar	
Iceland	1	NA	750 bar	
Worldwide	540	NA	-	

On its webpage, the Fuel Cells and Hydrogen Joint Undertaking present the state-of-the-art and future targets, termed the key performance indicators (KPIs), for hydrogen refueling stations as derived from the Multi-Annual Work Plan. Table 3 shows the selected KPIs. The international state-of-art is based on the year 2017. A full list of the indicators used can be found in the original source [88].

TABLE 3. SELECTED PARAMETERS FOR STATE-OF-THE-ART AND FUTURE TARGETS FOR HYDROGEN REFUELING STATIONS FOR FCH JU PROJECTS [88].

Parameter	Unit	State-of-the-art 2017	FCH 2 JU target 2024	FCH 2 JU target 2030
Lifetime	Years	10	15	20
Durability	Years	-	10	15
Energy consumption	kWh / kg	10	4	3
Availability	%	95	98	99
Mean time between failures	Days	20	72	168
CAPEX	EUR 1,000 / (kg/day)	7	3–1.6	2.4–1.3
Cost of renewable hydrogen	EUR / kg	12	9	6

With respect to the Japanese HRSs, the storage pressure corresponds to 820 bar and the dispensing pressure to 700 bar. Moreover, the cost figures from Japan are publicly available. As of March 2020, the CAPEX was JPY 330 million and the OPEX was JPY 31 million [89].

In Austria, the 350-bar hydrogen refueling station of HyCentA has a storage capacity of 17,600 l of liquid hydrogen and dispensers for liquid and gaseous hydrogen [90]. The 700-bar station from OMV features a 200 kg storage capacity [91].

In Germany, the price of hydrogen at all public stations corresponds to EUR 9.50 / kg, including value-added tax (VAT) [79].

Excluding the land cost, the investment and construction cost of domestic hydrogen refueling stations in China is reported to be CNY 15 million, among which the compressor, the storage tank and refueling system are the three main components, with the compressor accounting for the highest proportion of up to 32% [76].

4. Targets, Visions and Projections

This chapter presents selected announcements relating to the targets for infrastructure development for HRSs or the deployment of fuel cell vehicles for Asia, Europe and North America. Ultimately, the visions of Hydrogen Council are presented in order to give a perspective for the global numbers.

In some countries or regions, the targets are defined as visions or projections or as the components of roadmaps. In many countries, the targets for FCVs are included in the overall targets for zero-emissions vehicles. In such cases, where it is not possible to elicit precise figures for FCVs, the targets are not mentioned here; for a complete overview of the targets supporting electric vehicle development, refer to the IEA Global EV Outlook 2021 [92].

4.1. Asia

South Korea's Roadmap for the Hydrogen Economy, published in January 2019, outlines one of the most important national development plans for fuel cells and hydrogen. In this plan, the government defines a key role for the hydrogen economy to become the driving force of innovation growth in 2040. It is expected that the hydrogen economy will generate KRW 43 trillion in added value per year and 420,000 new jobs by then. The targets are summarized below, for the stated milestones [93], [94]:

- 2022: 81,000 FCVs (79,000 passenger cars and 2,000 buses) and 310 HRSs.
- 2040: 6.2 million FCVs (5.9 million passenger cars, 120,000 taxis, 60,000 buses, and 120,000 trucks) and 1,200 HRSs. The annual hydrogen supply reaches 5,260,000 tonnes.

It must be noted that the above-mentioned numbers refer to production numbers of vehicles used in the country and those exported. Excluding the exported units, 2.9 million passenger cars, 80,000 taxis, 40,000 buses, and 30,000 trucks are planned to be operated in South Korea by 2040.

The Basic Hydrogen Strategy of **Japan** lays out a vision for common targets that the public and private sectors should pursue together with an eye to achieving them by 2050. Among other important points, the strategy suggests that Japan should lead the world in realizing a hydrogen-based society. The key point of the national strategy includes concrete aims for 2025 and 2030 [95]:

- 2025: 200,000 passenger cars and 320 HRSs, with hydrogen stations made independent by the second half of the 2020s.
- 2030: 800,000 passenger cars, 1,200 buses and 900 stations.

Similar to South Korea and Japan, further ambitious plans have been developed in **China**. According to the revised version of the Hydrogen and Fuel Cell Vehicle Roadmap, the following targets are defined for China [96]:

- 2025: 100,000 fuel cell vehicles and 1,000 HRSs.
- 2035: The number of vehicles totals 1,000,000 units; the number of HRSs reaches 5,000 stations.

4.2. EUROPE

The European Union and several European countries have set out targets for hydrogen and fuel cells. The European Green Deal includes an action plan to boost the efficiency of resource use by moving to a clean, circular economy and restoring biodiversity, as well as cutting pollution with the aim of emitting net emissions of greenhouse gases by 2050 [97]. The EU Hydrogen Strategy defines a three-phase approach to develop renewable hydrogen, which can support the decarbonization of several sectors across Europe within an integrated energy system [98].

In the following, some of the selected targets are listed:

- At least 747 hydrogen refueling stations by 2025 in Europe [99].
- In the largest deployment in the continent to date, both Joint Initiative for Hydrogen Vehicles in Europe (JIVE) projects will see 291 FC buses on the roads by 2023 [100].
- The **French** National Plan aims for 5,000 passenger cars and commercial light-duty vehicles (LDVs), 200 buses and trucks, and 100 HRSs in 2023. The 2028 targets include 20,000–50,000 passenger cars and commercial LDVs, 800–2,000 buses and trucks, and 400–1,000 HRSs [101].
- **Croatia** aims for 25 HRSs in 2030, 50 in 2040, and 75 in 2050 [102].
- The Climate Agreement of the **Netherlands** aims to realize 15,000 passenger cars and 3,000 heavy-duty vehicles by 2025 and 300,000 passenger cars by 2030 [103].
- **Germany** set the target of increasing its HRS infrastructure to 400 stations by 2025 [104]. 14 passenger trains with fuel cell technology will also be in operation from 2021 and 27 additional units are planned by 2023 [105]. In its Hydrogen Roadmap, the Federal State **North Rhine-Westphalia** (NRW) aims to deploy more than 400 fuel cell trucks, at least 20 truck filling stations, 60 car filling stations, and 500 hydrogen buses for public transport by 2025 [106]. NRW's targets for 2030 include 11,000 fuel cell trucks over 20 tonnes, 200 filling stations for trucks and cars, 1,000 fuel cell waste bins, and 3,800 fuel cell buses for public transport only in NRW.
- In the Hydrogen Roadmap of **Spain**, the targets defined for the year 2030 include 5,000–7,000 light- and heavy-duty vehicles for goods transportation, 150–200 buses, two complete train lines operating with fuel cell trains, and 100–150 HRSs for public

use [107].

- In **Switzerland**, 1,600 heavy-duty trucks are planned for operation in 2025 [108].
- In **Italy**, 290,000 passenger cars and 3,600 buses are the targets for 2030 [109]. 346 HRSs for passenger cars and 96 for buses are also planned until then. In addition, Italy aims for 200,000 heavy-duty trucks in 2030 and an infrastructure of 40 HRSs for heavy-duty vehicles over the next six years [110], [111].

Finally, the **Hydrogen Roadmap Europe** prepared for the Fuel Cells and Hydrogen Joint Undertaking, representing the views of the industry represented by Hydrogen Europe, proposes the following milestones [98], [112]:

- By 2030: FCEVs could account for 1 in 22 passenger vehicles (with a total fleet of 3.7 million vehicles) and 1 in 12 light commercial vehicles (a total fleet of 500,000) sold, 45,000 trucks and buses, 570 trains, and with 3,700 HRSs in Europe.
- By 2040: 1 in 7 passenger vehicles and 1 in 5 light commercial vehicles (LCVs), 450,000 trucks and buses, 2,000 trains, and with 15,000 HRSs in Europe.
- By 2050, 45 million passenger cars, 6.5 million LCVs, 1.7 million trucks and 250,000 buses powered by hydrogen according to the ambitious scenario. In the business-as-usual scenario with no consolidated efforts, only 1.4 million passenger cars, 700,000 LCVs, 60,000 buses, and 380,000 trucks would be on Europe's roads. It would thereby not be possible to achieve the EU's climate goals and EU industry's position in the global economy under this scenario.

4.3. North America

Canada has defined the long-term vision of operating more than five million FCEVs and a hydrogen refueling network across Canada by 2050 as part of the Hydrogen Strategy for Canada, published in December 2020. As short- and medium-term targets, the Government of Canada set targets for the shares of zero-emission vehicles, which include battery-electric vehicles, FCEVs, and plug-in hybrid-electric vehicles [113].

The **U.S.** is targeting a nationwide 100% clean energy economy with net-zero emissions by 2050 [114]. Further to this, **California** will invest USD 20 million per year until 100 public HRSs are in operation [115]. By the end of 2025, California intends to have 200 stations in operation [116]. In this state, it is planned that 100% of the in-state sales of new passenger cars and trucks by 2035, 100% of medium- and heavy-duty vehicles by 2045, and 100% of off-road vehicles and equipment will be, where feasible, zero-emission [117].

The California Fuel Cell Partnership is pursuing an HRS infrastructure with the goals of 1,000 stations and 1,000,000 FCEVs by 2030 [118]. The California Air Resources Board estimates that the FCEV fleet will grow to 27,000 vehicles by 2023 and 48,900 by 2026 in California, based on the surveys of auto manufacturers' FCEV projections [116].

4.4. GLOBAL OUTLOOK

The rapid increase in interest in a hydrogen economy was captured in a recent report by the Hydrogen Council, with over 30 countries having hydrogen roadmaps and 228 large-scale hydrogen projects announced. Projections in this report showed that the costs for the renewable production of hydrogen could be in the range of USD 1.4–2.3 per kg. [119]
In its 2017 report, the Hydrogen Council presented the following vision for the worldwide deployment of fuel cell vehicles [120]:

- 2030: 1 in 12 cars in Germany, Japan, South Korea, and California to be powered by hydrogen; globally, 10–15 million cars and 500,000 trucks.
- 2050: Hydrogen would power more than 400 million cars, 15–20 million trucks, and around 5 million buses.

At the end of this chapter, the above-mentioned plans and visions are combined in a single chart in Figure 14 in an effort to present a complete picture of all targets and visions being realized by 2050.

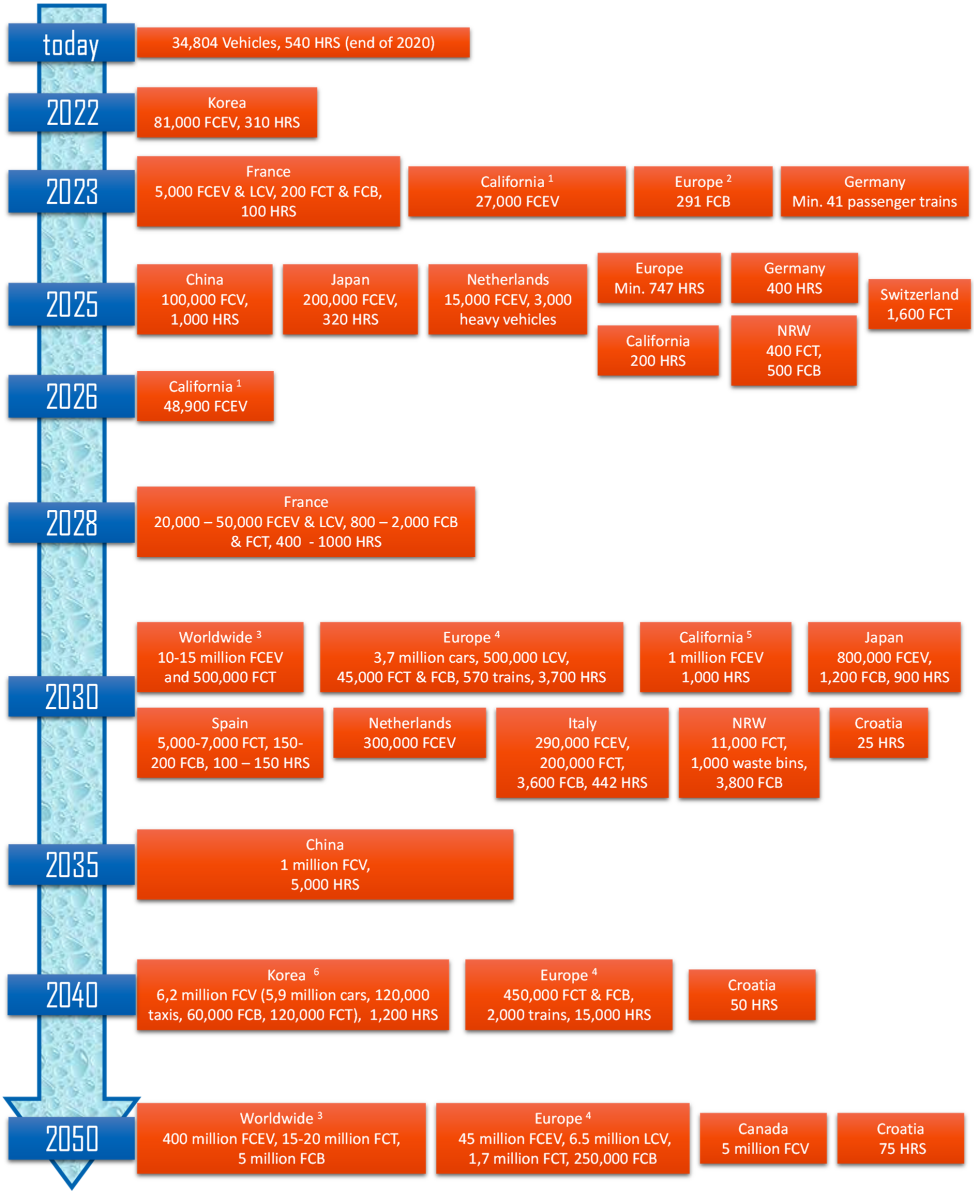

Figure 14. Selection of announced targets, visions and projections. FCEV: Fuel cell electric vehicle (passenger cars); FCV: Fuel cell vehicle (all categories); FCB: Fuel cell bus; FCT: Fuel cell truck; LCV: Light commercial vehicle; HRS: Hydrogen refueling station; NRW: Federal State of North Rhine-Westphalia, Germany; [1] CARB Estimation; [2] JIVE Projects; [3] Hydrogen Council Vision; [4] Hydrogen Roadmap Ambitious Scenario; [5] CAFP Vision; [6] Including exported vehicles.

5. CONCLUSIONS

In this document, the worldwide deployment status of FCVs in road transportation and HRSs as of the end of 2020 was presented and analyzed based on the results from the fourth survey of the Advanced Fuel Cells Technology Collaboration Programme, and complemented by additional information sources. As of 31/12/2020, the worldwide fleet of FCVs totaled more than 34,800. The fleet consists of passenger cars, buses, medium-duty trucks, light commercial vehicles, and heavy-duty trucks, in decreasing order. Globally, in 2020 South Korea became the first country to surpass 10,000 vehicles, followed by the U.S. and China with more than 9,000 and 8,000, respectively. About two-thirds of all currently deployed vehicles are on Asian roads. With almost 26,000 units, passenger cars still make up the highest share of all vehicle types, with a head-to-head competition between South Korea (10,041) and the U.S. (9,188). Adding Japan (4,100) as the third-ranking, 90% of the worldwide stock of fuel cell passenger cars is reached, shared across these three countries. As in the previous year, the worldwide fleets of buses and medium-duty trucks were dominated by the Chinese market. The increasing trends for both passenger cars and all other vehicle types slowed down in 2020. For passenger cars, the rate of increase dropped from 69% in 2019 to 37% in 2020, whereas the rate of increase for all vehicles dropped more strongly, from 95% in 2019 to 38% in 2020. For the strong increase rate among all vehicles in 2019, the increase in the number of buses and trucks in China was decisive. In 2020, this trend was halted due to changes in the national subsidy policy in China. The absolute increase in the number of passenger cars was only around 10% lower in 2020 than in the previous year, but the drop in the relative increase rate was stronger due to the increased population of vehicles on the road. Looking at the top two countries with the highest numbers of passenger cars, the development trends in the U.S. exhibited a limited increase of 15% in 2020 compared to 36% in 2019. In contrast, the number of registered passenger cars in South Korea increased very strongly, by 98% in 2020, contributing to more than half of the overall increase in the total number of fuel cell vehicles worldwide.

The AFC TCP survey also reveals that the number of HRSs had increased to 540 as of the reporting date of 31/12/2020, including public and private facilities. Japan, Germany and China are the three countries with the highest number of stations in operation. The public stations in Japan, Germany, China and the U.S. represent 63% of the total number of stations globally. In 2020, the increase rate of new stations slowed down to 15%, in comparison to 23% in 2019. Bringing the country-based numbers of registered vehicles and HRSs together, a theoretical analysis was performed to estimate the number of vehicles per station for the six countries with the highest numbers of stations. According to this analysis, South Korea has the highest allocation, with 194 vehicles per station, whereas France and Germany have the lowest, with around 10–12 vehicles per station. As the geographical location of the stations and the registration regions of the vehicles were not considered in this analysis, the real allocation profiles can lead to even higher, and respectively lower, numbers for both cases.

The regional, national and international roadmaps, targets and visions presented in this report show that the above-presented numbers reflecting the 2021 status can develop towards 2050, providing an essential contribution to zero-emission transportation with hydrogen fuel cells.

6. Acknowledgements and Disclaimer

Data collection by the Advanced Fuel Cells Technology Collaboration Programme (AFC TCP) Executive Committee Members.

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The results from the data collection on fuel cell vehicles and hydrogen refueling stations were originally provided for the publication of the International Energy Agency (IEA) Global EV Outlook 2021.

The presented data is intended to provide an overview of the status and perspectives and was prepared using the available sources. The AFC TCP does not claim that the data provided is complete.

The AFC TCP functions within a framework created by the IEA. The activities of the AFC TCP were coordinated by the IEA's Working Party on Energy End-use Technologies (EUWP). The views, findings and publications of the AFC TCP do not necessarily represent the views or policies of the IEA Secretariat or of its individual member countries.

Publication date: June 2021.

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8. APPENDIX

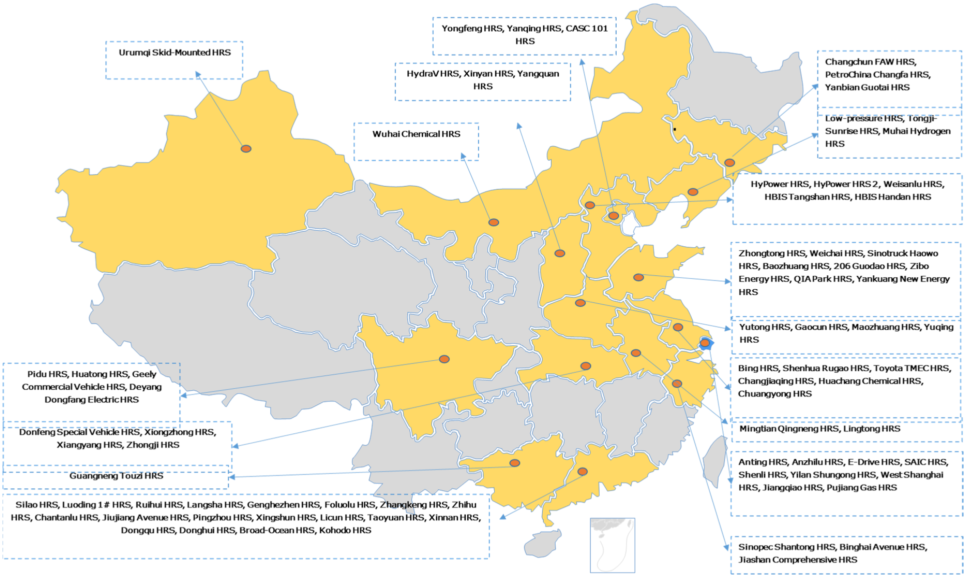

FIGURE A1. MAP OF LOCATIONS FOR HYDROGEN REFUELING STATIONS IN CHINA, PROVIDED BY CHINA SAE.

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